

A formation mechanism for the type II radio emission in the solar corona unrelated to shock waves

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Mark 4, COR1/STEREO and LASCO/SOHO data analysis shows that at least a portion of type II radio bursts observed in the corona occurs in the presence of a CME, but in the absence of a shock ahead of them. A drift current instability in the CME frontal structure is discussed as a possible cause of such bursts.

1. Introduction

Experiments have revealed the existence of a turbulence zone (“foreshock”) ahead of both the near-Earth shock [Cairns and Robinson, 1999] and interplanetary shocks travelling in the heliosphere [Bale *et al.*, 1999]. In the foreshock, there are fluxes of energetic particles (electrons and ions) which move away from the front along undisturbed magnetic field. They are the most energetic portion of the plasma heated in the shock front. As a result of beam instability evolution, electron fluxes excite Langmuir oscillations at the plasma electronic frequency. Due to the Rayleigh and Raman scattering [Zaitsev, 1965], these oscillations are transformed, respectively, into the first and second harmonics of the type II radio emission at the single and double plasma electron frequencies [Kuncic *et al.*, 2002]. Direct observations of the synchronous onset of increased Langmuir oscillations ahead of the interplanetary shock front as well as type II radio bursts at the same frequencies [Bale *et al.*, 1999] confirm the existence of this process. It is suggested that a similar process may take place for shocks excited by coronal mass ejections (CMEs). No direct evidence has so far been obtained, however, due to difficulties involved in recording a shock front in the corona. Recently developed methods for directly recording shock fronts in the corona [Eselevich and Eselevich, 2008; Eselevich, 2010] allow one to come closer towards solving this problem.

This study aims to demonstrate that, at least, a portion of type II radio bursts observed in the corona occur in the presence of CMEs, but in the absence of a shock ahead of them. A possible mechanism is discussed for the origin of such an emission associated with a drift current instability evolving in the leading edge of the CME frontal structure.

2. Input data and their representation

Our analysis employed coronal images obtained by Mark 4 (Mauna Loa Solar Observatory, <http://mlso.hao.ucar.edu>), COR1 (STEREO) [Howard *et al.*, 2008] and LASCO C2 (SOHO) coronagraphs [Brueckner *et al.*, 1995]. The data were represented in the form of difference brightness (polarization or full) $\Delta P(t) = P(t) - P(t_0)$, where $P(t)$ is the coronal brightness at moment t corresponding to the event under consideration, and $P(t_0)$ is the undisturbed brightness at fixed moment t_0 , selected as being well before the event start.

Difference brightness images were used to inspect the dynamics of a CME and its disturbed zone. Representations in the form of isolines ΔP , as well as sections both along the Sun radius at fixed position angles PA and non-radial sections at various instants were employed. Position angle PA is measured counterclockwise from the North Pole in the images.

3. Data analysis method

The analysis method is based on the results of recording the shock front in the corona [Eselevich, 2010]. Let us briefly review these results on the example of two CMEs with greatly different velocities: 5 May 1997 and 20 September 1997. Both these events are limb CMEs. Velocity with respect to the solar wind, u , for these CMEs is, respectively, 150 km/s and 700 km/s ($u = V - V_{SW}$, where V is the measured CME velocity, and V_{SW} is the solar wind velocity in the streamer belt). Figures 1A and B depict these CMEs in the form of difference brightness isolines, at a certain instant for each event. The frontal structure is nearly circular in shape (dashed circumferences in Figures 1A and 1B) for both the CMEs. The center of the circle, O, is R_C away from the center of the Sun along

the position angle PA_C . The direction from the frontal structure center is defined by angle α , measured counterclockwise from the CME direction (Figure 1B).

The differences between the slow and fast CMEs are conspicuous in both the images (Figures 1A and B) and the difference brightness profiles $\Delta P(R)$ plotted along the T+ propagation direction (section 1 in Figures 1A and B). These sections in Figures 1C and D are plotted in the frontal structure coordinate system, which allows the formation of a shock discontinuity to be traced practically unambiguously in both space and time [M. Eselevich, 2010]. One can see from Figure 1 that:

In the case of a slow CME ($u \approx 150$ km/sec), the difference brightness isolines are extend in the CME propagation direction. The difference brightness profile $\Delta P(R)$ in the disturbed zone ahead of the CME (black circles in Figure 1C) smoothly decreases with distance. There is practically no disturbed zone in the transverse direction $\alpha = -70^\circ$ (section 2, light circles).

In the case of a fast CME ($u \approx 700$ km/sec), the difference brightness isolines are nearly circular in shape. A discontinuity (jump) on the scale of $\approx 0.25 R_\odot$ (where R_\odot is the solar radius) is observed in the frontal part of the disturbed zone in the $\Delta P(R)$ profile (black circles in Figure 1D). Its position is indicated by a dashed bold line in Figure 1B.

This discontinuity was identified with the shock front based on the analysis of more than thirty limb CMEs with velocities $V \approx 200 \div 3000$ km/s. The analysis allowed the following steady regularity (law) to be discovered: “A disturbed zone extended along the CME propagation direction exists ahead of a coronal mass ejection when its velocity u with respect to the surrounding coronal plasma is below a certain critical velocity, u_C .

Shock formation ahead of the CME frontal structure in the vicinity of CME propagation direction depends on whether local inequality $u(R) > u_C \approx V_A(R)$ holds, which can be true at various distances $R \geq 1.5 R_\odot$ from the Sun center. Here, $V_A(R)$ is the local Alfvén velocity of slow solar wind in the streamer belt calculated in *Mann et al.* [1999].

The local Alfvén velocity, $V_A(R)$, is shown as a solid curve in Figure 2, with $V_{SW}(R)$ plotted as a dotted curve. These statements serve as a basis for identifying shocks in this study and their relation to the presence or absence of type II radio emission.

4. Event selection

The following three CMEs were selected for the analysis: 25 March 2008, 31 December 2007 and 3 June 2007. These events were investigated in detail in *Gopalswamy et al.* [2009] and have the following peculiarities:

1. These CMEs occur close to the limb when observed by all the instruments ("limb" events). The velocity values measured by Mark4, COR1a, b and C2 differ only slightly and are close to the radial velocity.
2. The white-light CMEs have the simplest and three-part structure most convenient for investigation: frontal structure (FS), decreased brightness region (cavity) and bright core [*Illing and Hundhausen*, 1986].
3. Their propagation in the corona was accompanied by meter and decameter type II radio bursts.

5. Analysis of shock presence/absence for three CMEs associated with type II radio emission

CME 1, 25 March 2008. Figure 3 shows the difference polarization brightness profiles $\Delta P(R)$ along the direction close to the CME motion axis ($PA \approx 100^\circ$), drawn using the Mark 4 data for three consecutive instants. Light circle profiles correspond to 18:41, directly prior to the CME appearing within the Mark 4 field of view (undisturbed corona).

The position of the point from which it was drawn (parameters PA_C and R_C specifying the approximate center of the frontal structure) and the direction (angle α) are indicated for each profile. For convenient comparison, the distances R from the Sun center are marked on the x axis. Additionally, the dashed bold line in the upper panel of Figure 3 depicts the profile $\Delta P(R)$ at 18:47 in the direction $\alpha = 95^\circ$ (sideward with respect to the CME motion direction). Its x position is calculated taking into account that the shape of the frontal structure is close to a circumference. In this direction, there is practically no disturbed zone ahead of the frontal structure, the frontal structure boundary (current sheet) having the size $\delta_I \sim 0.03 R_\odot$ (light gray on the profile), i.e. being close to the Mark 4 spatial resolution $K \approx 0.02 R_\odot$. The brightness jump δP_I at the frontal structure boundary has an amplitude close to the brightness jump amplitude δP_F at the shock front.

In the region of small α , there is a disturbed zone ahead of the frontal structure (shown by crosshatching in the profiles), bounded by a shock in the forefront (dark gray). (Shock propagation is seen in the following two plots in Figure 3). The disturbed zone being, in this direction, behind the shock front, it appears to include shock-heated plasma.

The shock front velocity, u , exceeds V_A (black squares in Figure 2) at all the distances. According to *Gopalswamy et al.* [2009] the meter type II radio emission is recorded when the forefront of the CME, corresponding to the shock, is at $1.7 R_\odot < R < 2.2 R_\odot$ (this part is crosshatched and labeled 1 in Figure 2). The decameter type II emission ceases to be recorded when the shock reaches $R \approx 3.6 R_\odot$ (vertical straight line in Figure 2). Hence the type II radio burst is accompanied by CME driven piston shock propagation, in this case.

CME 2, 31 December 2007. Figure 4A shows the difference brightness profiles based on the COR1a data at consecutive instants for this event. Unlike the profiles in Figure 3, they are drawn in the frontal structure coordinate system, namely [Eselevich M, 2010]:

1. each profile is normalized to its maximum value in the vicinity of the frontal structure (i.e. the maximum value of the normalized profile is 1);
2. each profile (except the very earliest one) is shifted along the x axis so that the positions of the frontal structure coincide for all the profiles.

Horizontal hatching shows the position of the frontal structure (the region of the normalized profile values > 0.5) in Figure 4A. For the initial instant 01:00, the difference brightness profiles for two angles α : 30° (diamonds) and 50° (dashed bold curve) - are shown in Figure 4A. The profiles are practically similar. No disturbed zone is perceptible ahead of the frontal structure for both of these directions. The steepest segment of the current sheet at the frontal structure boundary (light gray) in the direction $\alpha = 50^\circ$ has a characteristic spatial scale $\delta_I \sim 0.02-0.03 R_\odot$, comparable to the COR1 spatial resolution $K \approx 0.016 R_\odot$. At the next instant 01:05 (asterisks in Figure 4L) the disturbed zone

increases only slightly in the direction $\alpha = 30^\circ$. Thus the current sheet of the frontal structure remains practically undisturbed prior to this instant. Its velocity u only slightly exceeds V_A (light triangles in Figure 2). At the subsequent instants (01:10 and 01:15, not shown in Figure 4L), the disturbed zone continues to gradually increase, a jump – a shock with the front width δ_F – eventually forming in the very forefront of the zone. It is shown in dark gray color for the instants 01:20 (crosses) and 01:30 (triangles). Such a change in the profile is absent in the direction $\alpha = 50^\circ$.

Unlike the faster CME 1, where a horizontal segment of the $\Delta P(R)$ profile (i.e. $\Delta P(R) \approx \text{const}$, Figure 3) is observed directly behind the front, this event exhibits no steady state directly behind the shock front even for the very latest instant 01:30 (triangles), since the difference brightness increases as the distance decreases. This may possibly mean that the shock front has been in the forming stage up to the instant in question. The encircled solid triangles correspond to it in the plot $u(R)$ in Figure 2. It is only at large distances $R > 4 R_\odot$ (non-encircled black triangles in Figure 2) that a steady shock front is recorded (a segment with $\Delta P(r) \approx \text{const}$ is observed directly behind the front). The meter type II radio emission [Gopalswamy *et al.*, 2009] is recorded when the forefront of CME 2, corresponding either to the current sheet at the frontal structure boundary or to the forming shock wave, is at $1.5 R_\odot < R < 2.6 R_\odot$ (crosshatched segment labelled 2 in Figure 2). The decameter type II emission ceases to be recorded when the forefront of the CME, corresponding to the shock, reaches $R \approx 3.5 R_\odot$ (vertical line in Figure 2).

CME 3, 3 June 2007. The difference brightness profiles $\Delta P(r)$ for this event are shown in Figure 4B. These profiles are based on the COR1a data, in the frontal structure

coordinate system in the direction $\alpha = 0^\circ$ for the two consecutive instants 09:35 (crosses) and 09:55 (triangles). These two profiles exhibit the evolution of the disturbed zone (shown by crosshatching). There is no shock. For comparison, the dashed bold line shows the profile $\Delta P(r)$ at 09:45 plotted in the sideward direction $\alpha = -60^\circ$. The steepest segment, at the frontal structure boundary, in this profile has a difference brightness jump, δP_I , which is larger than the half of the maximum brightness on the scale $\delta_I \sim 0.02 R_\odot$, comparable to the COR1 spatial resolution.

The velocity of the forefront of the disturbed zone is lower than V_A (light circles in Figure 2) at practically all the distances. The meter and decameter type II radio emission (shown by crosshatching 3 and vertical line in Figure 2) is recorded when the forefront is at $1.7 R_\odot < R < 2.6 R_\odot$, with no shock signatures observable in the difference brightness profiles.

Therefore, even though the type II radio bursts were observed in all the three events in question, the initial stage of the burst was not related to the shock in the CME 2 case, while no shock was observed in the CME 3 case. Thus, analysis of the last two CMEs – 2 and 3 – allows one to conclude that, at least, a portion of type II bursts may occur in the absence of CME-excited shocks. Can the observed radio bursts be caused by a different source?

6. Discussion of a possible shock-unrelated mechanism for the type II radio emission in the solar corona

Note, first of all, that a magnetic field jump δB_I must correspond to a brightness jump δP_I on the same spatial scale δ_I at the CME frontal structure boundary under the

conditions of rarefied magnetized coronal plasma. Drift current instability at the CME frontal structure boundary (similarly to drift current instability at the laminar shock wave front [Zaitsev, 1965]) may serve as the possible cause of plasma oscillations (subsequently transforming into radio emission). The condition $V_d > V_{Te}$ must be satisfied for such oscillations to be excited, where V_d and V_{Te} are, respectively, the drift and thermal electron velocities [Chen, 1984]. Let us estimate their values.

The drift velocity can be estimated from the Maxwell equation: $V_d \approx \delta B_I c / 4\pi e N \delta_I$, where δB_I and δ_I are, respectively, the amplitude and scale of the magnetic field jump, c is the light speed, N is the electron density, e is the electron charge. If the CME is regarded as a “magnetic barrier” moving in the solar wind, then $\delta_I \sim u / \omega_{ei}$ in rarified plasma, where $\omega_{ei} = e\delta B_I / c(m_i m_e)^{0.5}$ is the hybrid cyclotron frequency [Longmire, 1963]. Here, c is the light speed, e is the electron charge, m_i and m_e are the ion and electron mass, respectively. Assuming $u \sim V_A$, we obtain $\delta_I \sim c / \omega_{pe}$, where $\omega_{pe} = (4\pi N e^2 / m_e)^{0.5}$ is plasma electron frequency. This allows the electron drift velocity in the current sheet at the CME frontal structure boundary to be estimated as:

$$V_d \approx \delta B_I c / 4\pi e N \delta_I \approx \delta B_I / (4\pi N m_e)^{0.5}.$$

Let B_0 be undisturbed magnetic field directly ahead of a CME. According to the calculations by Chen [1996] and heliospheric observations by Lin *et al.* [2008], the ratio $(\delta B_I + B_0) / B_0$ can be around 2-3 and, correspondingly, $\delta B_I / B_0 \approx 1-2$. Presumably, the ratio $(\delta B_I + B_0) / B_0$ should not vary significantly as a CME moves in the corona and heliosphere away from the Sun. Therefore, we obtain $\delta B_I \approx (1-2) B_0 \approx (1-2) \text{ G}$ for $B_0 \approx 1 \text{ G}$ in the corona.

Taking density $N \approx 3 \times 10^6 \text{ cm}^{-3}$ as an estimate for the streamer belt at $R = 2 R_{\odot}$, and given $\delta B_I \approx (1-2) \text{ G}$, we may estimate the drift velocity $V_d \approx (5-10) \times 10^4 \text{ km/s}$ at the CME boundary. At the same time, the thermal electron velocity $V_{Te} \approx 5 \times 10^3 \text{ km/s}$, for the coronal temperature $T_e \approx 1.5 \times 10^6 \text{ K}$, i.e. the condition $V_d > V_{Te}$ is satisfied.

Thus, the type II radio bursts observed in the CME 2 and CME 3 events may be caused by a drift current instability evolving at the CME frontal structure boundary.

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Figure 1. A and C, slow CME 5 May 1997; B and D, fast CME 20 September 1997. A and B, difference brightness isolines, L is the position angle, the coordinate axes are in units of R_{\odot} . C and D, difference brightness distributions depending on distance r , measured from the CME frontal structure center (point O), along two different sections 1 and 2, whose direction is shown by dashed lines in the top panels. LASCO C2 data.

Figure 2. Velocities $u = V - V_{SW}$ relative to the surrounding SW depending on the distance from the Sun center for the CME frontal structure (light symbols) or for a shock ahead of the CME (black symbols) in the propagation direction. Black triangles inside the circles correspond to the shock front at, presumably, the forming stage. Dashed curve is velocity V_{SW} of quasi-stationary slow solar wind in the streamer belt in *Wang et al.* [2000]. Solid curve is the Alfvén velocity in the streamer belt in *Mann et al.* [1999].

Figure 3. Difference polarization brightness profiles $\Delta P(R)$ at consecutive instants based on Mark 4 data for the 25 March 2008 CME. Light circle profiles correspond to the undisturbed corona. To the right of each instant are shown the parameters indicating the profile position in the image: its reference point (PA_C , R_C) and direction (angle α).

Figure 4. Difference brightness profiles $\Delta P(r)$ in a coordinate system tied to the frontal structure at consecutive instants based on COR1a data: A) 31 December 2007 CME; B) 3 June 2007 CME. The inscriptions are as in Figure 3.